Sun, Xiuxiu and Liang, Xingyu and Zhou, Peilin and Qian, Yuehua and Liu, Teng and Liu, Bo (2017) Effect of miller cycle and fuel injection strategy on performance of marine diesel engine. In: 11th Asia-Pacific Conference on Combustion, ASPACC 2017, 2017-12-10 - 2017-12-14. ,

11th Asia-Pacific Conference on Combustion,
The University of Sydney, NSW Australia
10th -14th December 2017.

Effect of Miller Cycle and Fuel Injection Strategy on Performance of Marine Diesel Engine

Xiuxiu Sun[1,3], Xingyu Liang[1], Peilin Zhou[3], Yuehua Qian[2], Teng liu[2], Bo Liu[2]

[1]Affiliation

1. State key Laboratory of Engines, Tianjin University, Tianjin 300072, China

[2]Affiliation

2. China Shipbuilding Power Engineering Institute Co. Ltd, Shanghai 200120, China

[3]Affiliation

3. Naval Architecture, Ocean &Marine Engineering, University of Strathclyde, Glasgow G4 0LZ, UK

Abstract

The computational fluid dynamic (CFD) model is presented to investigate the performance of large two-stroke marine diesel engine. The simulated model is validated with the experiment data. The in-cylinder pressure of simulated model is agreement with the experiment data. The errors of NO_x and CO_2 are also in accepted range. The effect of Miller cycle, injection sequence and pilot injection are investigated on the combustion and emissions using this model. The results show that the in-cylinder pressure decreases with deeper of Miler cycle level. However, The NO_x has a slight reduced. The quantity of decreased NOx is not satisfy the requirement of Tier Ⅲ. We also found that the injection interval angle augment of two injectors makes the combustion pressure decrease. The NO_x is decreased to 8.95 g/kWh. However, the ISFC is higher 7.3 g/kWh compared with base value when the injection interval angle is 8 ° CA. The appropriate pilot injection strategy can decrease the NO_x and ISFC, such as P10I5. These methods are not reduced the quantity of NOx to meet the requirement.

1 Introduction

The environment protection has been attention by more and more people. The marine diesel engine emissions are limited strictly. The International Maritime Organization (IMO) Tier III limits NOx emissions to 3.4 g/kWh in the emission control areas, which is a 76% reduction compared with the 14.4 g/kWh stipulated in Tier II [[1]. The Tier III [2]is more strictly for the quantity of NOx. So, more measures are used in marine diesel engine for reducing the emissions, such as exhaust gas recirculation (EGR), selective catalytic reduction (SCR), injection strategy and Miller cycle.

Numerical simulation technology has been widely used, because they are efficient in terms of human and financial resource. Kontoulis et al. [3] used the KIVA-3 code as a modeling platform to study the effects of advanced injection strategies. By adding an appropriately timed pilot injection, they achieved fuel savings of approximately 1.7%, without increasing NO_x emissions. Verschaeren et al. [4] investigated NO_x emissions in a medium-speed heavy-duty diesel engine using EGR and Miller timing. An injection advance during low-load operation raised combustion pressures and shortened combustion duration, lowering CO droop and PM emissions and increasing efficiency. Chen et al. [5] studied pilot injection for improvement of combustion characteristics in a heavy-duty diesel engine. Their results demonstrated that with the advance of pilot injection timing, the peak in-cylinder pressure is declined, the ignition delay of the main combustion is shortened, and the NO_x and soot emissions are reduced, whereas the HC and CO emissions are increased. The injection strategy has large effect on marine engine performance and emissions. So, it is necessary to research different reducing NO_x methods.

This paper analyzed the effect of Miller cycle, injection sequence and pilot injection on the marine diesel engine performance and emission. The computational fluid dynamic (CFD) is validated with experimental data. The in-cylinder pressure and emissions are compared for different measures. The potential of reducing NO_x is analyze. This paper provides guide direction to choosing appropriate method for researchers to droop the quantity of NO_x.

2 Numerical Model

2.1 Marine engine CFD model

The present CFD model is conducted on the 6S35ME-B9. The structure parameter can found in the table 1. The CFD model was established on this structure using CONVERGE 2.3 software.

cylinder number	6
Bore (mm)	350
Stroke (mm)	1550
Displacement (L)	149
Connecting rod length (mm)	1550

Speed (r/min)	142
Power (kWh)	3575

Table1: 6S35ME-B9 test engine specifications

Figure 1 shows the three-dimensional structure of model. This model includes a scavenge box, cylinder and exhaust port. The k-ε two-equation mode is used as turbulence model. Kelvin Helmholtz-Rayleigh Taylor model is applied to the simulation of spray breakup. The NTC collision model is implemented to simulate the fuel collision. The wall splash model is used in the O'Rourke model based on Weber number, film thickness and viscosity. The detailed chemical solver combustion model is used to simulate the fuel ignition. For the emissions generate models, the Extend Zeldovich NO_x model is applied to simulate the production of NO_x. Hiroyasu-NSC Model is used to simulate soot production respectively. Those models are chosen in CONVERGE. The injected liquid temperature is set to 345 K. The injection duration is 15.36°CA and the total injection mass is 0.0126 kg, which was obtained from experimental data.

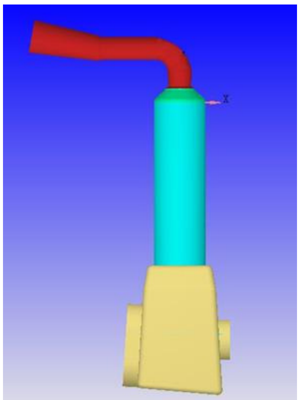

Figure 1:The three-dimensional geometric structure

The CFD model is based upon continuity, momentum and energy conservation laws [6]. Mesh grid size is decided based on the desired calculation time and calculation accuracy. Grid control includes a base grid, adaptive mesh refinement and fixed embedding. The effect of the base grid and the adaptive mesh refinement are shown in Fig. 2. As seen in Fig. 2 (a), the compression pressure of base grid 0.04 m is in agreement with that of base grid 0.03 m. The calculation accuracy increases gradually with decreasing base grid size. If the adaptive mesh refinement is set to 4, the calculated pressure is in good agreement with the experiment data, as shown in Fig. 2 (b). However, the calculation time also increases. Setting the base grid to 0.04 m and the adaptive mesh refinement to 4 can ensure the accuracy of the simulation.

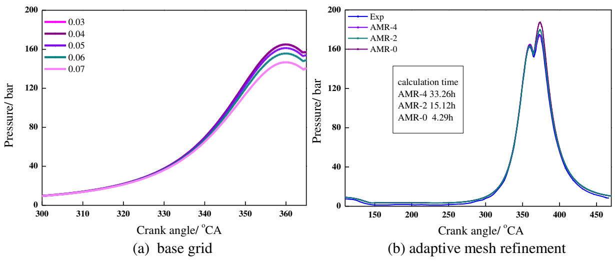

Figure 2: The effect of grid on the pressure: (a) base grid (b) adaptive mesh refinement

The CFD model will be used in the simulation. The simulated value was validated with the experimental data.

2.2 Model Validation

The in-cylinder pressure and emissions were tested when the engine speed is 142 r/min and the load operated 100 %. The calculated value was validated with the experimental data. Stratsianis et al.[7] researched the post-injection on the effect of marine diesel engine performance. The simulated value also validated with the experimental data under the 100 % load. Fig.1 shows the comparison of in-cylinder pressure between in simulation and experiment.

Figure 3 shows the in-cylinder pressure comparison between the calculated value and experimental data. The errors of maximum pressure during compress and combustion process are 0.8% and 1.5%, respectively. The time of change pressure delay is 0.846°CA for the model. The in-cylinder pressure is in good agreement with the experimental data. The model can accurate predicts the pressure of marine diesel engine.

The NO_x and CO_2 emissions are also compared to validate the accuracy of model, which are shown in Fig 4. For NO_x, the error is 2.8% compared with simulation and experiment value, which is acceptable for predicting the quantity of NO_x. The error for CO_2 is larger than that for NO_x. The single component n-tetradecane is used as alternative fuel to simulate the combustion process. And, the new n-tetradecane mechanism is reduced for decreasing the calculated time. Some reactions are disappeared for CO_2 produce mechanism. The quantity of NO_x is close to the experimental data, that is to say: the CFD model can accurate predict the quantity of NO_x using n-tetradecane as alternative fuel.

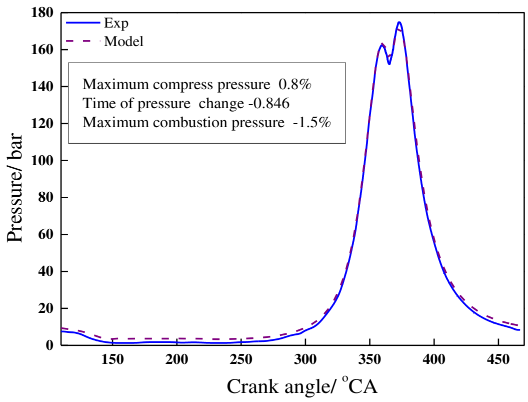

Figure 3: Comparison of in-cylinder pressure for the simulation and experiment

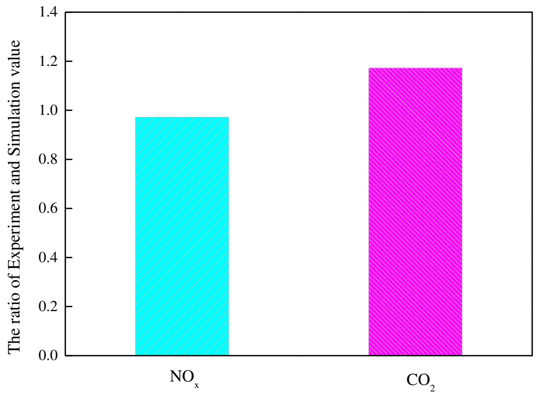

Figure 4: Comparison of NO_x and CO_2 for the simulation and experiment

3 Results and Discussion

3.1 Effect of Miller Cycle

The decreased inlet gas temperature causes the NO_x production less. The Miller cycle makes the in-cylinder gas temperature lower. The result can be realized by delaying the close time of exhaust valve for the two-stroke marine diesel engine.

The different Miller cycle patterns were simulated to research the effect on the marine diesel engine performance and emissions. The 5° CA was used as interval angle of exhaust valve delay close time. So, the four methods were named as M5, M10, M15 and M20. The scavenging pressure was improved to offset the loss of fresh charge. Fig.5 shows the changes of intake pressure and air-fuel ratio under different Miller cycle. The intake pressure increases with delaying of exhaust valve close time, which can makes the equivalence ratio almost same for the Miller cycle.

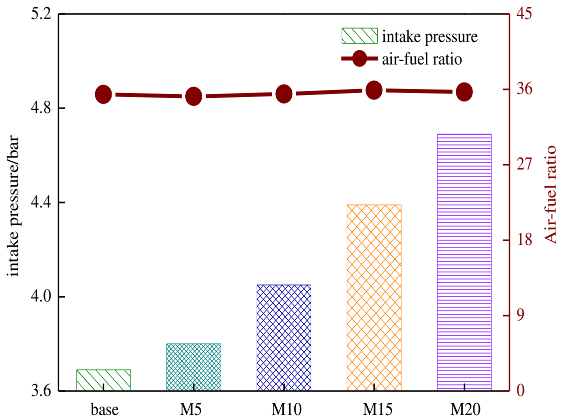

Figure 5：The changes of intake pressure and air-fuel ratio using different Miller cycle

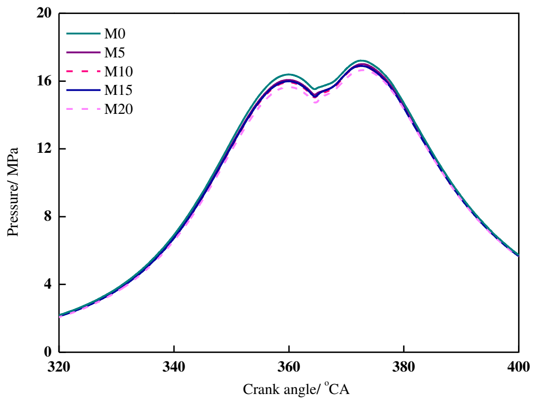

Figure 6：The changes of in-cylinder pressure using different Miller cycle

Figure 6 shows changes of the in-cylinder pressure with crank angle using different Miller cycle. It can be seen that the in-cylinder pressure decrease with the exhaust valve close time delay. The augmented intake pressure makes the in-cylinder pressure higher than that of the original engine in the bottom dead center (BDC) nearby. Because, the equivalence ratio of different cases are almost same.

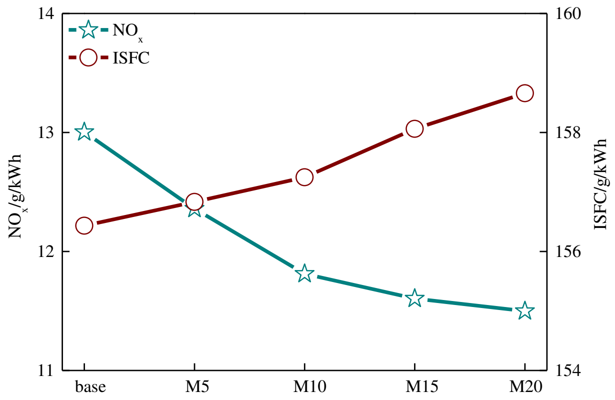

Figure 7：The changes of NO_x and ISFC using different Miller cycle

The changes of NO_x and ISFC are shown in Fig.7. The in-cylinder temperature decreases with exhaust valve close time delay. The fresh charge reduces residual gas temperature. And, The NOx are produced in higher temperature and rich oxygen condition. The range of high temperature shrinks gradually along with Miller cycle level deepening. The quantity of NO_x decrease 11.5 % than that of original engine. However, it is a great deal of different compared with require of Tier III. The ISFC increases with the exhaust valve close time delay. The compress pressure decreases during compress and power stroke (Fig.6). So, the indicated power also reduces. However, the injection fuel mass is constant. These make the ISFC increasing.

3.2 Effect of injection sequence

The marine diesel engine performance also was analyzed under the different injection sequence. Two injectors were distributed uniform on the cylinder head. Two injectors were injected at the same time for the original engine. The different interval angles were investigated between in two injectors. The interval angles of two injectors were set to 2°CA, 4°CA, 6°CA and 8°CA.

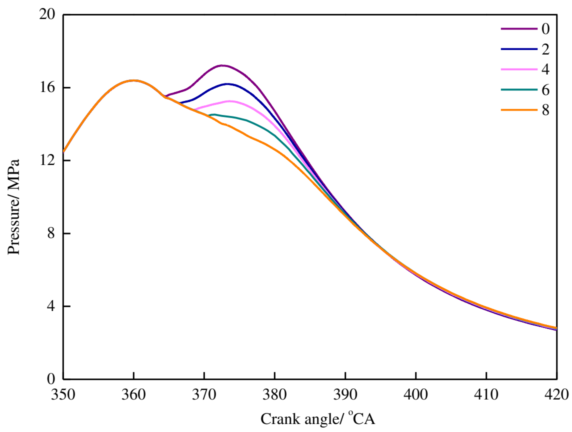

Figure 8：The changes of in-cylinder pressure using different injection sequence

The variations of in-cylinder pressure are shown in Fig.8 for the different injection sequence. It is obvious that the maximum combustion pressure is decreased with increasing the interval angles of two injectors. The increasing pressure is caused by the fuel combustion after the top dead center (TDC). The maximum combustion pressure drops with interval angle of two injectors increasing. And, the combustion pressure peak value nearly disappears when the injection interval angles set to

8 °CA. The less fuel will be burn after the top dead center. The degree of combustion will decrease. So, the in-cylinder pressure will decrease. .

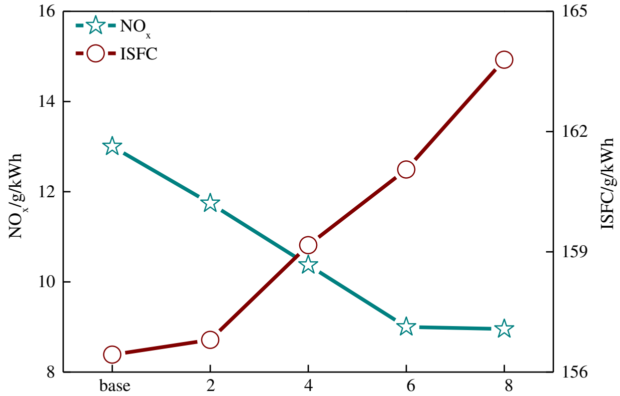

Figure 9：The changes of NO_x and ISFC using different injection sequence

Figure 9 shows the variations of NO_x and ISFC using different injection sequence. The trend of NO_x decreases with the interval angles augment of two injections. The quantity of NO_x is reduced by 4.05 g/kWh when the interval angles increases to 8°CA. The more fuel was uncompleted burn with increment of interval angles. The changes of in-cylinder pressure can explain this phenomenon. The lower temperature makes the NO_x production less. The injection mass is constant. The ISFC is inversely proportional to the power. The lessened combustion pressure also makes the power decreased. So, the ISFC increases with augment of interval angles.

In conclusion, the interval angles augment of two injections reduces the quantity of NO_x. The decrement of NO_x is larger using injection sequence than the value using Miller cycle. However, the increased of ISFC is also large. The method is not advised to reduce the quantity of NO_x using injection sequence.

3.3 Effect of pilot injection

The pilot injection measure was widely used to reduce the NO_x. Bae et al. [8] studied the effect of pilot injection on combustion and emission characteristics in a marine diesel engine. The results show that variation of pilot injection timing affects auto ignition and heat release rate. Huang et al. [9] also invested the effect of pilot injection on low temperature combustion in diesel engine under a medium EGR rate. The decrease in pilot-main interval can greatly reduce NO_x emission and ISFC. So, the effect of pilot injection will be researched on the performance of marine diesel engine in this paper. The pilot injection quantity and interval time were investigated for reducing the NO_x. Table 2 shows the investigated conditions. The pilot injection quantity is 5 %, the interval time of pilot and main injection is 5 °CA. This condition will be named P5I5. The same naming pattern were used in others conditions.

Pilot injection quantity	Interval time (°CA)		
5 %	5	10	15
10 %	5	10	15
15 %	5	10	15

Table2: the pilot injection quantity and pilot interval

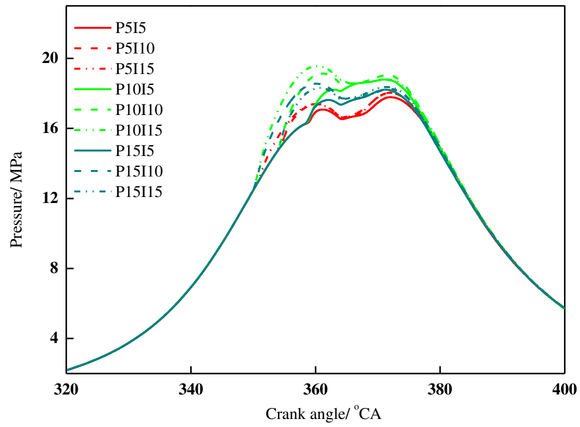

Figure 10：The changes of in-cylinder pressure using pilot injection strategy

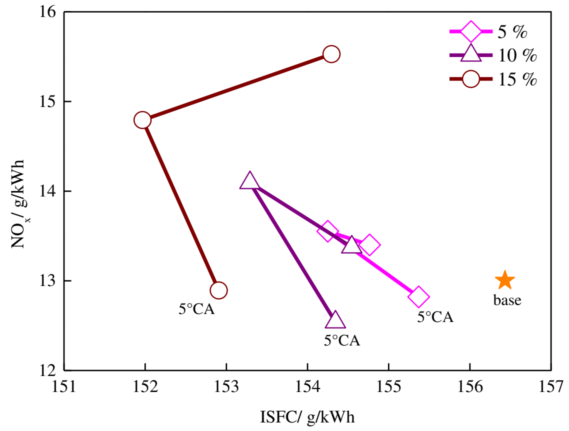

Figure 11：The changes of NO_x and ISFC using pilot injection strategy

The comparisons of in-cylinder pressure are shown in Fig.10. It can be seen that the in-cylinder pressure increases with the argument of pilot injection quantity and interval time. The fuel was burn during compress stroke, which cause the in-cylinder pressure increasing. Due to the quantity of fuel lessen in power stroke, the in-cylinder pressure is almost same for different pilot injection quantity and interval time.

Figure 11 shows the compared relationship between NO_x and ISFC using pilot injection strategy. It can be seen that the ISFC decreases with the augment of interval time of pilot and main injection. The ISFC has lower value when the interval time of pilot and main injection is 15°CA. The P10I5 has minimum NO_x value. Nevertheless, the ISFC is medium. However, the simulated value of NOx and ISFC are lower than the base value for the case P10I5. So, The P10I5 is an optimum method considering the quantity of NOx and ISFC. The quantity of NO_x and ISFC are lower than that of base calculated.

In conclusion, the pilot injection can be used to reduce the NO_x for the marine diesel engine. However, the reduced value of NO_x and ISFC are less than these values using Miller cycle and injection sequence. That is to say: the pilot injection method needs to used coupling others strategy, which can reduces NO_x to the required value of Tier Ⅲ .

4 Conclusions

The CFD model of marine diesel engine was established in this paper. The model was validated with the experimental data. Then, the effect of Miller cycle, injection sequence and pilot injection were investigated on the combustion and emission of marine diesel engine. The results as follows:

1. The in-cylinder pressure and emissions by calculated by CFD model were in agreement with the experimental data.
2. The in-cylinder pressure decreases with the exhaust valve close time delay. The NO_x also decreases. However, the decrement of NO_x is less. It is not meet the requirement of Tier Ⅲ.
3. The in-cylinder pressure and NO_x decreases with the injection interval angles augment of two injectors. The NO_x is reduced to 8.95 g/kWh when the injection interval angle set to 8°CA.
4. The in-cylinder pressure increases using the pilot injection. The P10I5 has minimum value of NO_x and ISFC. The pilot injection methods needs to used coupling others strategy.

5 Acknowledgment

This work was supported by National Natural Science Foundation of China (No. 51376136 and No. 91641111) and National Sci-Tech Support of China (2016YFC0205304). The author also wants to appreciate the support of high-tech Ship Research Program of MIIT.

References.

- http://www.DieselNet.com/standards, Emission Standards, IMO Marine Engine, 13.07.2017(2017).
- Herdzik, J., Emissions from marine engines versus IMO certification and requirements of tier 3. Journal of KONES Powertrain and Transport, 18(2011)
- C.C.L.K. P. Kontoulis, The international symposium on diagnostics and modeling of combustion in intern al combustion engines 1(2008).
- R. Verschaeren, W. Schaepdryver, T. Serruys, M. Bas tiaen, L. Vervaeke, S. Verhelst, Energy 76(2014) 614-621.
- L. Chen, H. Zeng, X.B. Cheng, Applied Mechanics a nd Materials, 651-653(2014)866-874.
- A.A. Amsden, P.J. Orourke, T.D. Butler, Nasa Sti/rec on Technical Report N, 89(1989)
- Stratsianis, V., P. Kontoulis and L. Kaiktsis, Effects of Fuel Post-Injection on the Performance and Pollut ant Emissions of a Large Marine Engine. 2(2016).
- M.Bae1.D SikHan.Y J. Chang.J H Song.C H Jeon,,Jo urnal of the Korean Society of Marine Engineering,(2 010)37-45.
- HZ Huang, QX Wang, C Shi, QS Liu, CZ Zhou, Ap plied Energy, 179 (2016) 1194–1208

JOURNAL TITLE

11th Asia-Pacific Conference on Combustion

MANUSCRIPT TITLE

Effect of Miller Cycle and Fuel Injection Strategy on Performance of Marine Diesel Engine

Dear editor, reviewer

Thank you very much for your useful comments and suggestions on our manuscript. We have modified the manuscript accordingly, and the detailed corrections are listed below point by point:

<u>Response to the editor and reviewers</u>

- ✓ The whole manuscript has been revised carefully. The revisions and corrections have been highlighted in red color according to your requirement.
- ✓ Besides, the language in manuscript has been revised by professional.

<u>Response to reviewer</u>

Reviewer #1:

I have tried to read this manuscript a couple of times, and unfortunately, because of the poor English and poor sentence structure the meaning of many of the sentences is lost to me. This unfortunately is making it very difficult to provide a sufficient judgement on the quality of the paper. For now, I am recommending it be revised, as with a very significant editing of the manuscript it is possible it can ultimately be at an acceptable level, otherwise if the authors do not make significant changes I recommend it is rejected.

- ✓ Dear reviewer, we had revised the manuscript carefully. The manuscript has also been proofread by English speaker. Thank you very much.

I would recommend that the authors have the paper very thoroughly proofread by an English speaker. Generally, the paper is poorly structured which makes it very difficult to go from one section to the next. The knowledge gap and new contribution is also very unclear. There are also insufficient references (and they should be numbered, not listed as bullet points).

- ✓ Dear reviewer, we had revised the manuscript carefully. Three methods have been researched to reduce the emissions of marine diesel engine in this paper. The in-cylinder pressure and emissions of marine diesel engine have been analyzing in every section. This provides direction for researchers to reduce the NOx meeting the requirement of Tier III.

- ✓ We also added the number of reference to descript the significant of this paper. However, the references have been listed using bullet point. Because, this is requirement of the ASPACC2017.
- ✓ Thank you for your advices.

Examples of poor sections of the paper:

1. In the abstract it is stated "…the injection interval angles augment of two injectors makes the combustion terrible". This is very far from technical and accurate writing. What exactly does it mean if "combustion is terrible"? Reference to "terrible combustion" is also present in section 3.2, i.e. "The increment of interval angles causes the combustion terrible".

- ✓ Dear reviewer, the sentence has been advised. The unreasonable expressions have been revised in manuscript. Thank you very much.

2. Much of section 3.3 is unfortunately difficult to follow. Particularly after Fig. 8, and this is again due to poor English. Sentences like "the in-cylinder compresses pressure increase" do not make sense, and this is only one example, many others throughout the manuscript, thereby making it too difficult for the reader to comprehend the technical value of sections of the paper.

3. Additionally, In section 2.2 the authors state that the errors of "maximum compress pressure and combustion are 0.8% and 1.5%, respectively". What is the "error in combustion", this is extremely vague, but this may just be poor sentence structure? I cant be sure. I believe the authors mean they are comparing maximum in-cylinder pressure during combustion???

Other issues:

1. It is understood that there is little space in 4 pages to elaborate on a CFD model, but the authors have presented almost nothing, including no references to the modeling approaches, which is not acceptable if they are not going to present their methodology here. There is no information on the mesh resolution, how it was chosen, what the timestep is…The only information provided is that it is a "kappa-epsilon" two equation model. This in my opinion, is not to the standard required. Another passing statement on how soot production is modeled is also provided, but given that the entire paper is based on CFD, I cant possibly recommend acceptance without further information in this section.

2. That being said, the authors do present some validation with experimental data later, which seems to be reasonable at least for the data presented however this is only done for one specific engine condition. I am not sure what the justification for this is. Is this a common testing condition? This must be explicitly defined here. Can we expect other conditions to yield similar comparisons to CFD, why or why not? With the lack of references as well,

these questions remain unanswered.

3. The y-axis of Fig. 2 is not sufficient. It needs to be explicitly defined what is being normalized here. a y-axis label of “Experiment/Simulation” as a vertical dimensionless number is not acceptable.

4. A reference is needed to the “Tier III” requirements.